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MAKING WAVES
(Postprint)

Edward W. Cliver

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14. ABSTRACT
Carley, et al., (2013) link together the key elements for acceleration of particles by magnetohydrodynamic shocks at the Sun for an eruptive event on 22 September 2011. In brief, in this event the lateral expansion of a coronal mass ejection drove a quasi-perpendicular shock wave that accelerated electrons in intermittent bursts, with the intermittency attributed to the rippled or wavy surface of the shock front. The history of research on large-scale solar waves is reviewed. Such waves were discovered by radio means in 1947. Recent progress has been primarily based on high-cadence images of such waves at extreme ultra-violet wavelengths.

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SOLAR PHYSICS

Making waves

High-cadence images link the phenomena required for particle acceleration at the Sun. A plasmoid-driven shock wave accelerates electrons in intermittent bursts.

Edward W. Cliver

Shock waves are a primary mechanism for the acceleration of particles at the Sun and in other astrophysical settings, such as supernovae. Shocks at the Sun and in the heliosphere offer the best chance to investigate the shock particle-acceleration process in detail. Eoin Carley and his co-workers, as they now report in *Nature Physics*[1], have used high-cadence solar images and radio spectroscopy to link together the key elements of particle acceleration at a solar shock wave: a driving plasmoid or coronal mass ejection (CME); a propagating coronal bright front at the leading edge of the CME with an associated metric radio 'type II' burst — the classic signature of a solar shock; and the coronal and interplanetary electrons accelerated at the shock. They present evidence that the shock is quasiperpendicular and attribute the bursty or quasiperiodic nature of the radio emission emanating from the type II burst to a rippled or wavy shock surface.

On 22 September 2011, a CME — an erupting bubble of magnetized plasma — was observed off the limb of the Sun. The eruption was recorded by coronagraphs and extreme-ultraviolet (EUV) imagers on the Solar and Heliospheric Observatory (SOHO), the Solar Dynamics Observatory (SDO) and the Solar Terrestrial Relations Observatory (STEREO), as well as by ground-based radio telescopes. Carley *et al.* used coronagraph images from SOHO (near Earth) and STEREO-B (lagging ~95° behind Earth in a 1 AU orbit) to identify a faint front off the southern flank of the laterally expanding CME as a shock wave. At the same location, SDO high-cadence EUV images revealed a coronal bright front propagating southwards along the limb of the Sun in concert with an imaged type II radio source. The radio spectrogram of the event exhibited a 'herringbone' structure emanating from a nondrifting (constant frequency) backbone, suggesting electron acceleration by a shock wave moving parallel to the Sun's surface.

Taken together, these observations indicate a quasiperpendicular shock wave (propagating normal to the ambient magnetic field) driven by the lateral expansion of a CME. The shock accelerates electrons, which flow inwards towards the Sun and outwards into the interplanetary medium on upstream open field lines. The electron streams produced herringbones with 2–11 s periodicities. Carley *et al.* suggest that a rippled shock surface modulated the efficiency of electron acceleration in this event, resulting in the observed time structure.

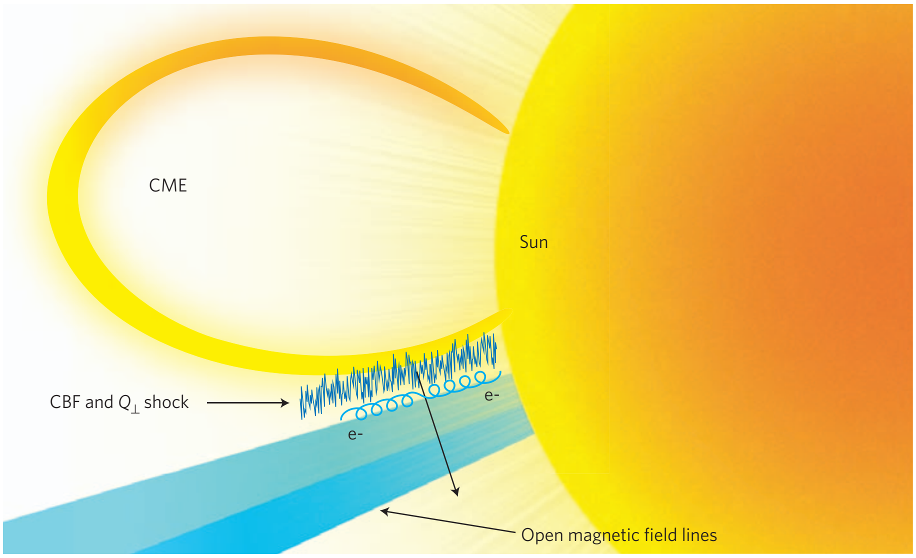

Figure 1 | Coronal mass ejection. The CME observed on 22 September 2011 drove a coronal bright front (CBF) and quasiperpendicular ($Q_\perp$) shock southwards along the limb of the Sun. Shock-accelerated electrons escape to interplanetary space along open field lines.

The study of large-scale waves on the Sun began in the late 1940s with the discovery of metric type II radio bursts that are characterized by a drift to lower frequencies at a rate of ~0.5 MHz s^{-1} (ref. 2). The causative disturbance, later identified as a magnetohydrodynamic shock wave, propagates outwards through the corona with a speed of 500–750 km s^{-1}. The optical counterparts of type II bursts — observed in 6563-Å emission from hydrogen — propagate along the solar surface with comparable speeds[3]. In a key development, it was proposed that the compression of the chromosphere that is responsible for the optical wave is due to the 'sweeping skirt' of a coronal type II shock wave[4]. In 1998 research on large-scale solar waves was given fresh impetus when the EUV telescope on SOHO detected coronal waves[5]. Large-scale waves were subsequently reported in soft X-rays, 10830-Å emission from helium atoms and microwaves. A close kinematical relationship between the various manifestations of large-scale waves implied a common origin[6].

In the past several years, solar scientists have used the new high-cadence imagery from the STEREO spacecraft (launched in 2006) and SDO (from 2010) to establish a strong link between CMEs and large-scale waves[7]. In short, CMEs drive these waves. Progress in this area includes recognition of the importance of the lateral (rather than radial) expansion of CMEs for surface wave creation[8], culminating in the unambiguous identification of a quasiperpendicular type II shock wave at the Sun by Carley and team[1] (Fig. 1). In addition, a clear distinction is forming between moving EUV phenomena (called pseudo waves) associated with the CME itself as a result of field line stretching

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or magnetic restructuring[9], and true waves that are initially driven by the CME and later become freely propagating when the lateral expansion of the CME stops[10,11].

The work of Carley and colleagues also impacts research on the acceleration of solar energetic particles, or SEPs, by shock waves. At present, the surface structure of shocks, including ripples, is beyond the reach of solar imagery but, as demonstrated by Carley *et al.*, the macro-geometry (quasiparallel or quasiperpendicular) can be determined with confidence in certain cases. The potential importance of shock orientation for SEPs was fully appreciated only recently when compositional signatures of quasiparallel and quasiperpendicular shock acceleration in large SEP events were identified[12]. In a recent examination of a CME, EUV wave, and SEP event on 21 March 2011[13], evidence from SEP composition near-Earth measurements was reported that was consistent with the picture presented in ref. 12 although confirming radio images of a shock wave were not available. The outlook for radio imagery is promising, given the development of the Low Frequency Array in Europe and the Murchison Widefield Array in Australia. In combination with the high-cadence EUV images from STEREO and SDO, the imaging and spectroscopy capabilities of these new radio telescopes will permit more detailed study of the shock particle-acceleration process and provide a probe of the medium through which the shocks propagate[14]. ❐

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